

WHY THE LAWS OF PHYSICS ARE JUST SO

Ulrich Mohrhoff

Sri Aurobindo International Centre of Education

Pondicherry 605002 India

ujm@satyam.net.in

Does a world that contains chemistry entail the validity of both the standard model of elementary particle physics and general relativity, at least as effective theories? This article shows that the answer may very well be affirmative. It further suggests that the very existence of stable, spatially extended material objects, if not the very existence of the physical world, may require the validity of these theories.

1 INTRODUCTION

If at all a fundamental physical theory be derived, it is by teleological arguments—from what it is good *for*. It has been suggested, for instance, that the laws of physics are preconditions (conditions of possibility) of empirical science [1]. They might, instead, be preconditions of observers, of life, or of chemistry. This article presents arguments in support of the view that both the standard model of elementary particle physics (SM) [2] and general relativity (GR) are preconditions of an “interesting” world, defined by Squires [3] as one that contains chemistry. It further suggests that the very existence of stable, spatially extended material objects, if not the very existence of a physical world, may require the validity of the SM and GR, at least as effective theories.

It is well known, but rarely sufficiently appreciated, that matter owes its stability at least in part to the indefiniteness of the relative positions between its constituents. Section 2 shows that the proper way of dealing with indefinite properties or values leads straight to the existence of a unique density operator and the familiar trace rule of quantum mechanics (QM). Section 3 explains why the vector space of QM must be complex. Section 4 derives the local metric structure of the world, which is described by special relativity. Section 5 demonstrates that the only possible effects on the motion of a scalar particle are those represented by the vector potential A and the metric tensor g . Section 6 traces the steps leading to quantum field theory in general and to quantum electrodynamics (QED) in particular, argues that QED and GR are necessary but not sufficient for chemistry, and presents arguments in support of the following: The electroweak and

strong forces— $U(1)\otimes SU(2)\otimes SU(3)$ —together with GR constitute the simplest theoretical structure consistent with chemistry. Sections 7 and 8 put forward arguments suggesting that the very stability of matter, if not the very existence of the physical world, implies both the SM and GR.

The final sections address a couple of related issues. Section 8 suggests that the final theory envisaged by Weinberg [4] and others may be nothing more than the best *effective* theory, and Sec. 9 argues that perhaps we don’t need a quantum theory of gravity, inasmuch as all that such a theory would allow us to do is investigate the world on scales that do not exist.

2 THE ORIGIN OF THE TRACE RULE

An obvious feature of our world is the stability of matter. By this I mean the existence of spatially extended material objects that neither explode nor implode the moment they are formed. It is well known that matter owes this feature in part to the indefiniteness of the relative positions between its constituents; together with the exclusion principle it “fluffs out” matter [5].

The importance of indefiniteness for the obvious stability of matter can hardly be overstated. This makes it an excellent starting point for a derivation of the laws of QM. As is explained elsewhere [6, 7, 8], the proper way of dealing with variables with indefinite values is to make counterfactual probability assignments. If an observable is said to have an “indefinite value,” what is meant is that it does not have a value (inasmuch as no value is indicated) but that it would have a value if one were indicated, and that positive probabilities are associated with at least two possible values.

The most important feature of observables with indefinite values is that their values are *extrinsic*. Since the indefiniteness of an observable implies that it sometimes does and sometimes does not have a value, a criterion is called for, and this is the existence of a value-indicating fact—an actual event or state of affairs from which the value can in principle be inferred. An observable with extrinsic values possesses a value only if, and only to the extent that, a value is indicated by a fact [6, 8]. (Since only a fact can indicate something, the words “by a fact” are of course redundant.) Specifically, *no position is a possessed position unless it is an indicated position*.

What else can we deduce from the existence of observables with indefinite values? Let me begin by denouncing a didactically disastrous approach to QM. This starts with the observation that in classical physics the state of a system is represented by a point \mathcal{P} in some phase space, and that the system’s possessed properties are represented by the subsets containing \mathcal{P} . Next comes the question, what are the quantum-mechanical counterparts to \mathcal{P} and the subsets containing \mathcal{P} *qua representations of an actual state of affairs and possessed properties*, respectively? Once we accept this as a valid question, we are on a wild-goose chase.

If at all we need to proceed from classical physics, the proper way to do so is to point out that every classical system is associated with a probability measure, that this is represented by a point \mathcal{P} in some phase space, that observable properties are represented by subsets, and that the probability of observing a property is 1 if the corresponding subset contains \mathcal{P} ; otherwise it is 0. Next comes the question, what are the quantum-mechanical counterparts to \mathcal{P} and the subsets containing \mathcal{P} *qua representations of a probability measure and observable properties*, respectively? Once we have the answer to this we are ready for the next question: Is it possible to reinterpret the quantum-mechanical counterpart to \mathcal{P} as representing an actual state of affairs connoting a set of possessed properties? Because the classical probability measure assigns trivial probabilities (either 0 or 1), it is possible to think of it as an actual state of affairs. Because quantal probability measures generally assign nontrivial probabilities (neither 0 nor 1), it is not possible to similarly reinterpret the quantum counterpart to \mathcal{P} .

To find the quantum counterpart to \mathcal{P} , all we have to do is make room for nontrivial probabilities, and the obvious way to do this is to replace the subsets of a phase space by the subspaces of a vector space, or by the corresponding projectors. An atomic probability measure will then be a 1-dimensional subspace U , probability 1 will be assigned to properties that contain U , probability 0 to properties that are orthogonal to U , and the remaining properties will be associated with nontrivial probabilities. The possible values of an observable will evidently correspond to an orthogonal resolution of the identity, and compatible attributions of properties will be represented by projectors that are sums of projectors from an orthogonal resolution of the identity—that is, by commuting projectors. Finally, the probability assigned to the sum of two orthogonal projectors will be the sum of the probabilities assigned to the individual projectors. This is nothing but the classical sum rule for the probability of “either A or B ,” which holds if A and B are members of a set of mutually exclusive events, provided that one of them happens. Since probabilities are assigned on the proviso that a value be indicated, this condition is always satisfied.

All of the above follows directly from the obvious way to make room for nontrivial probabilities—namely, the substitution of subspaces for subsets and 1-dimensional subspaces for points. It is sufficient to prove Gleason’s theorem [9, 10] for real and complex vector spaces with more than two dimensions [11], according to which probability assignments based on earlier value-indicating facts are governed by the familiar trace rule and a unique density operator. The theorem has recently been proved for two dimensions as well [12, 13, 14]. The question as to why QM needs a *complex* vector space will be answered in the following section.

3 WHY COMPLEX NUMBERS?

Consider a series of measurements. (A measurement is anything that results in an actual event or state of affairs from which the possession of a property by a physical system or a value by a physical variable can in principle be inferred.) If we assign probabilities to the possible results of the final measurement, we have to do so in conformity with the probability algorithm derived in the previous section. If the intermediate measurements are not performed but the histories that lead to a possible result of the final measurement are defined in terms of the possible results of the intermediate measurements, the probability of any possible final result will, according to that algorithm, be given by the (absolute) square of a sum over all the histories that lead to this result. Each history contributes an amplitude, which may be real or complex.

Next consider the limit of a series of unperformed position measurements on a scalar particle, in which the histories become continuous trajectories. Suppose s parametrizes such a trajectory, and ds_1 and ds_2 label adjoining infinitesimal segments. Our probability algorithm requires us to multiply the amplitudes associated with successive segments of a history, so that

$$A(ds_1 + ds_2) = A(ds_1)A(ds_2). \quad (1)$$

Hence the amplitude for propagation along an infinitesimal path segment can be written as $A(ds) = \exp(z ds)$, and the amplitude for propagation along a path \mathcal{C} can be written as $A(s[\mathcal{C}]) = \exp(zs[\mathcal{C}])$. If z had a real part, the probability of finding the particle anywhere would not be conserved; it would either increase or decrease exponentially with time. It follows that $A(s[\mathcal{C}])$ must be a phase factor $\exp(ibs[\mathcal{C}])$.

4 THE ROAD TO SPECIAL RELATIVITY

Consider a scalar particle and a particular continuous path. As the particle travels along this path (in our imagination if nowhere else), s increases, and $\exp(ibs)$ rotates in the complex plane. Let us say that every time it completes a cycle, the particle “ticks.” If the particle is free, it singles out a class of uniform time parameters—those for which the number of ticks per second is constant. Different particles may tick at different rates, which are related to the standard rate of one tick per second by the species-specific constant factor b .

So much for the origin and meaning of mass and proper time. Our next task is to determine the physical roots of the spatial part of the metric. An analysis of two-slit interference experiments (in the framework of standard QM) [15, 16] has shown that physical space cannot be a self-existent and intrinsically differentiated expanse. Space is the totality of positions that are possessed by material objects, and since these are relatively defined, there are no absolute positions. By the same token, there is no absolute rest. As a consequence, the proper-time interval ds and inertial coordinates are related

via

$$ds^2 = dt^2 + K(dx^2 + dy^2 + dz^2), \quad (2)$$

where K is a universal constant, which may be positive, zero, or negative [17].

Here are some of the reasons why $K > 0$ can be excluded. (i) Ubiquitous causal loops: Reversing an object’s motion in time is as easy as changing its direction of motion in space. (ii) The nonexistence of an invariant speed—a speed that is independent of the inertial frame in which it is measured—rules out massless particles, long-range forces, and the possibility of resting the spatial part of the metric on the cyclic behavior of particles (the rates at which they tick). The last point is decisive, in as much as all there is to fix the spatial part of the metric is the rates at which free or freely falling particles tick. Since space is not a self-existent and intrinsically differentiated expanse, the metric has to be defined—as well as brought into existence—by the behavior of the world’s material constituents. And the only thing that a scalar particle does is tick as time passes. This cyclic behavior realizes (makes real) the temporal part of the metric. Hence if there is to be a spacetime metric, its spatial part must be determined by its temporal part.

If K is not positive, causal loops are ruled out by the existence of an invariant speed. For $K = 0$ this is infinite, and for negative K it is $c = \sqrt{1/|K|}$. The problem with the nonrelativistic case $K = 0$ is that the rates at which free particles tick still cannot fix the spatial part of the metric. They just define a universal inertial time scale via $ds = dt$. Nor are light signals available for converting time units into space units. Nor do we get interference from free particles since $\exp(ibs[C])$ is the same for all paths with identical endpoints—and without interference QM is inconsistent (with the existence of a macroworld, which it presupposes [6, 8, 15]). It is possible to obtain interference via an action that depends on the frame, but if all there is to fix the spatial part of the metric—for every inertial frame—is the cyclic behavior of free or freely falling particles, this ought to be invariant. And for this we need a finite invariant speed (negative K).

5 THE CLASSICAL FORCES

The rates at which particles “tick” not only found the metric properties of the world but also make it possible to influence the behavior of matter by influencing particle propagators. The only way of influencing the probability of finding at one spacetime location a scalar particle last “seen” at another location, is to modify the rate at which it ticks as it travels along each path connecting the two locations. The number of ticks associated with an infinitesimal path segment defines a species-specific Finsler geometry $dS(dt, d\mathbf{r}, t, \mathbf{r})$ [18, 19]. As the following will show, there are just two ways of influencing the Finsler geometry that goes with a scalar particle.

As mentioned, the stability of matter rests on both the indefiniteness of relative positions and the exclusion principle [5]. For the exclusion principle to hold, the ultimate constituents of matter must be indistinguishable members of one or several species of

fermions. The necessary indistinguishability entails that all free particles belonging to the same species of fermions tick at the same rate. This guarantees the possibility of a global system of spacetime units [20]: While there may be no global inertial frame, there will be local ones, and they will mesh with each other as described by a Riemannian spacetime geometry. Accordingly there is a species-specific way of influencing the Finsler geometry associated with a scalar particle, which bends geodesics relative to local inertial frames, and there is a species-independent way, which bends the geodesics of the Riemannian spacetime geometry. In natural units:

$$dS = m\sqrt{g_{\mu\nu}dx^\mu dx^\nu} + qA_\nu dx^\nu, \quad (3)$$

where A and g represent the two possible kinds of effects on the motion of scalar particles.

If the sources of these two fields have no definite positions, the fields themselves cannot have definite values. We take this into account by summing over histories of A and g , and for consistency with the existence of a macroworld (presupposed by QM [6, 8, 15]) we make sure that a unique history is obtained in the classical limit. Obvious and well-known constraints then uniquely determine the terms that need to be added to dS (except for a possible cosmological term) [21].

We have reached an inconsistency, which no physical theory proposed so far has been able to eliminate. Since we sum over histories of g , none of the continuous paths contributing to a particle propagator has a definite spacetime length. And since the spacetime lengths of these paths constitute the physical basis of the metric properties of the world, definite distances or durations do not exist. But the spacetime points on which g as a field depends can only be defined by the spacetime distances that exist between them. If definite spacetime distances do not exist, the manifold over which field theories are constructed does not exist either. (Renormalization is a way of glossing over this inconsistency.)

6 THE STANDARD MODEL

Huygens' principle tells us that a sum over spacetime trajectories can be replaced by a wave equation. A relativistic wave equation has "negative energy" solutions corresponding to particles for which proper time decreases as inertial time increases [22], and it conserves charge rather than probability. Particle numbers are therefore variables, and since the quantities that dynamically influence their values are fuzzy, so are they.

To accommodate fuzzy particle numbers we sum over the histories of a field the Lagrangian of which yields the wave equation in the classical limit. This turns the field modes into harmonic oscillators whose quanta represent individual particles with definite energies and momenta. Expanding the interaction part of $\exp(iS)$ yields a sum over histories in which free particles are created and/or annihilated, and by using the appropriate wave equation for spin-1/2 particles we arrive at the Feynman rules for QED. (The wave

equation for a free particle is obtained by imposing on the wave function a specific relation between the energy E and the absolute value p of the momentum. This too is a consequence of the fact that the spatial part of the metric is determined by its temporal part—the rates at which free particles tick. For spin-1/2 particles the relativistic relation between E and p leads to the Dirac equation. A half-integral spin is required by the stability of matter since the exclusion principle only holds for fermions.)

Gravity and electromagnetism are clearly necessary for a world that contains something as interesting as chemistry. Without the electromagnetic force there would be no Periodic Table, and without gravity there would be no stars to synthesize the Table's ingredients beyond helium. But the two classical forces are not sufficient. Nucleosynthesis calls for another force. The requirement of renormalizability pretty much narrows this down to a non-Abelian gauge field. *A posteriori* we know that three colors suffice. Why not less? One reason is that two would not lead to confinement. There would be no nucleons for making a variety of nuclei and no residual force that is both attractive and short-range—capable of binding nucleons into nuclei and incapable of spoiling the delicate electromagnetic equilibria on which the Periodic Table depends. Thus three colors are needed as well as sufficient, which fixes the Lagrangian for quantum chromodynamics [23], give or take a few adjustable parameters.

Yet another force is needed, for several reasons. If stars did not explode, the elements beyond helium would remain confined to the interiors of stars, where they are created. The force responsible for stellar explosions—the weak force—has the simplest non-Abelian gauge group. It also plays an important role in nucleosynthesis and critically controls the primordial fusion of hydrogen into helium. Since $SU(2)$ does not lead to confinement, and since the stability of matter forbids the weak force to cause the decay of atomic electrons through interactions with nuclear quarks, a different mechanism for reducing its range is needed—the Higgs mechanism [24]. Moreover, the electron's flavor-doublet partner must be neutral if the weak force is to trigger stellar explosions [25].

Thus once again one is left with little choice. The non-conservation of parity remains something of a mystery, as does the triplication of flavor pairs, but there are indications that both are needed to create the required excess of matter over antimatter [2, 26]. (The total annihilation of both matter and antimatter would spell the total annihilation of all spatiotemporal relations and thus the total annihilation of space and time.)

While these arguments are certainly not rigorous, they nevertheless make it plausible that the SM and GR together constitute the simplest theoretical structure consistent with a world that contains chemistry. It seems that we do live in the simplest possible interesting world [3]. In the following two sections I shall submit stronger claims, namely that the stability of matter may call for a world in which the SM is at least an effective theory (Sec. 7), and that such a world may be the only possible physical world (Sec. 8).

7 THE STABILITY OF MATTER AND THE STANDARD MODEL

The “anthropic” principle [25, 27] is usually invoked to account for (i) the approximate values of some of the SM’s 19+ adjustable parameters and (ii) certain rather special cosmological initial conditions. What the previous sections have shown, or strongly suggest, is that the entire SM (including GR and the general theoretical framework of quantum field theory) has teleological underpinnings. It not only describes almost all known physical phenomena (exceptions are the recently observed neutrino masses, if confirmed, and the as yet unknown nature of dark matter [28]) but it also appears to contain nothing but the simplest set of physical laws permitting the existence of something as interesting as chemistry.

Laws that are at least effectively identical with the SM may follow from a weaker requirement. The stability of matter (as defined at the beginning of Sec. 2) rests on the indefiniteness of relative positions. The search for the right formalism for dealing with indefinite variables takes us straight to QM. But QM would be inconsistent without macroscopic objects, inasmuch as no position is a possessed position unless it is an indicated position (Sec. 2), and only a macroscopic object can indicate something. (The reason why only macroscopic objects can be indicators is that only the positions of macroscopic objects can be consistently thought of as forming a self-existent system of causally connected properties that are effectively detached from the facts by which they are indicated [6, 8, 15].) The stability of matter thus entails the existence of macroscopic objects in general and of macroscopic detectors in particular. But it may well be that macroscopic detectors can exist only in worlds that contain a sufficient variety of chemical elements. If this turned out to be the case, the stability of matter would require chemistry. Hence it would entail physical laws that are (at least effectively) identical with the SM (including GR). In short:

$$\text{Stable Matter} \longrightarrow \text{QM} \longrightarrow \text{Detectors} \xrightarrow{?} \text{Chemistry} \longrightarrow \text{SM+GR}$$

8 THOUGHTS ON A FINAL THEORY

In the context of the SM only certain quite unlikely values of the adjustable parameters and the cosmological initial conditions are consistent with the phenomenology encapsulated in the Periodic Table. To some this suggest design, to others it suggests the existence of an ensemble of universes across which parameters and initial conditions take random values, while to the majority of theoretical physicists it suggests the need for a final theory which allows most of the actual parameter values to be derived from first principles, and which either stipulates the initial conditions [29] or makes the universe largely insensitive to them [30].

I can see another possibility. Supposing that chemistry is indeed required for the existence of detectors (and thus for the stability of matter), a world governed by laws that are not (effectively) identical with the SM will be void of detectors, as will be a world with the “wrong” parameter values and/or cosmological initial conditions. But a world without detectors is a world without positions, and a world without positions is a spaceless world. And since a spaceless *physical* world is a contradiction in terms, we can conclude that *any* physical world will (at least effectively) be governed by the SM and GR. For the same reason we cannot conceive of universes with the “right” parameters and initial conditions as members of an ensemble across which parameters and/or initial conditions vary. Universes with the wrong parameters or initial conditions are logically inconsistent and therefore nonexistent. Nor can we infer design if only worlds with the right parameters and initial conditions are logically consistent.

What about the possibility of a final physical theory that leaves no room for “anthropic” adjustments? If the cognitive apparatus of the human mind is up to the task of discovering the true structure of the world, we can expect that this will eventually be discovered. And if this structure—or a part of it—admits of a precise mathematical description, it may well turn out to be faithfully represented by such a theory. But the human mind may not be up to that task, and the true structure of the world may not be mathematical. In either case *all* physical theories would be effective approximations to the true structure of the world, which would remain forever beyond our ken. There could still be a final theory, but it would simply be the best effective theory, and it could contain as reminders of its effective nature such inconsistencies as the one pointed out at the end of Sec. 5.

Elsewhere [8, 15] I argued that the world is constructed from the top down, by a finite spatial differentiation that stops short of realizing the multiplicity of a manifold, rather than built from the bottom up, on an intrinsically and maximally differentiated manifold, out of locally instantiated properties. There are psychological as well as neurobiological reasons [31, 32] to believe that the physically inadequate bottom-up approach is intrinsic to the human mind. If so then it appears that we cannot hope for more than an optimal effective theory.

9 A QUANTUM THEORY OF GRAVITY?

The search for a final theory is in large measure a search for a quantum theory of gravity. Yet there are reasons to believe that the idea of such a theory is self-contradictory, as the following will show.

As a rule, the indefiniteness of a variable cannot evince itself without something less indefinite. The indefiniteness of the position of a material object can evince itself (through statistical fluctuations) only to the extent that detectors with sharper positions exist. The residual fuzziness of the positions of macroscopic objects cannot evince itself, which is

why these positions are effectively intrinsic [6, 8, 15].

Again, the indefiniteness of the electromagnetic field can evince itself to the extent that distances are well-defined. The fuzziness of A induces an indefiniteness in the species-specific lengths (Sec. 5) of the histories (paths) associated with electrically charged particles, and so does the fuzziness of g . On observationally accessible scales the indefiniteness induced by A far exceeds that induced by g . Down to scales on which g becomes as fuzzy as A , distances are well-defined. This is why the fuzziness of A has observable consequences such as the Lamb shift. (This effect exists not only because a 2S electron is closer to the proton on average than is a 2P electron but also because on atomic scales “closer” is still extremely well defined.)

On the other hand, there is nothing less fuzzy than the metric. This suggests to me that there are no physical effects that are due to the indefiniteness of the metric, just as there are no physical effects that are due to the indefiniteness of the positions of macroscopic objects. If so, a quantum theory of gravity would allow us to study the physical consequences of a fuzziness that lacks physical consequences. Such a theory would make it possible to investigate the physics on scales that do not exist, for on scales on which the fuzziness of g becomes significant, the concept of “scale” loses its meaning.

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